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Two Recent Results on B Physics from CDF

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Preliminary results from two recent CDF b physics analyses are presented. The first obtains $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$ from a measurement of the asymmetry in $B^0, \overline{B^0} \to J/\psi\, K^0_S$ decays, providing the best direct indication so far that CP invariance is violated in the b sector. The second obtains new results on the parity even (A_0 and $A_{\|}$) and odd ($A_{\perp}$) polarization amplitudes from full angular analyses of $B^0 \to J/\psi\, K^{*0}$ and $B^0_s \to J/\psi\, \phi$ decays:

$$B^0 : \left\{ \begin{array}{lcl} A_0 & = & 0.770 \pm 0.039 \pm 0.012 \\ A_{\|} & = & (0.530 \pm 0.106 \pm 0.034) e^{(2.16 \pm 0.46 \pm 0.10)i} \\ A_{\perp} & = & (0.355 \pm 0.156 \pm 0.039) e^{(-0.56 \pm 0.53 \pm 0.12)i} \end{array} \right.$$

$$B^0_s : \left\{ \begin{array}{lcl} A_0 & = & 0.778 \pm 0.090 \pm 0.012 \\ A_{\|} & = & (0.407 \pm 0.232 \pm 0.034) e^{(1.12 \pm 1.29 \pm 0.11)i} \\ |A_{\perp}| & = & 0.478 \pm 0.202 \pm 0.040 \end{array} \right.$$

1 Introduction

A rich program in b production and decay physics has been pursued with data collected by CDF in Run I (1992 – 1995). By making use of a silicon strip vertex detector and the copious production of various species of b hadrons at the Tevatron $\bar{p}p$ collider, we have obtained precise measurements of the B^0, B^+, and B_s^0 lifetimes and the B_s^0 mass. We have observed the decay $B_c \to J/\psi \ell \nu$, and set the most stringent limits on the decays $B_{d,s} \to \mu^+ \mu^-$ and $B \to K^{(*)} \mu^+ \mu^-$. We also have obtained competitive measurements on neutral B mixing and ratios of branching fractions for selected b hadron decay modes. Most of these results and others have been published or submitted for publication.[1]

Preliminary results from two more analyses have become available this year. The first analysis builds upon and significantly extends the previously published CDF result[2] on the CP nonconserving parameter $\sin(2\beta)$ as determined from the asymmetry in $B^0, \overline{B^0} \to J/\psi K_S^0$ decays. The analysis presented here includes events that are not fully reconstructed in the silicon vertex detector, thereby doubling the available data sample, and uses the combination of three flavor tagging algorithms.

The second analysis obtains results for the polarization amplitudes in the pseudoscalar to vector-vector decays $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$. These results are relevant to understanding the decay dynamics of hadrons containing a heavy-quark and provide information relating to the possible use of these decays for studies of CP invariance violation. For example, if the decay $B^0 \to J/\psi K^{*0}$ were to occur in a parity eigenstate (even or odd) followed by the CP invariant decay $K^{*0} \to K_S^0 \pi^0$, then this mode could be used as simply as the $B^0 \to J/\psi K_S^0$ mode for determining $\sin(2\beta)$.

2 Improved Measurement of $\sin(2\beta)$ with $B^0 \to J/\psi K_S^0$ Decays

It has long been recognized[3] that a measurement of the CP noninvariant asymmetry

$$A_{CP}(t) = \frac{\frac{dN}{dt}(\overline{B^0} \to J/\psi K_S^0) - \frac{dN}{dt}(B^0 \to J/\psi K_S^0)}{\frac{dN}{dt}(\overline{B^0} \to J/\psi K_S^0) + \frac{dN}{dt}(B^0 \to J/\psi K_S^0)}$$

provides a phenomenologically clean method for determining $\sin(2\beta)$. Violation of CP invariance can arise in the Standard Model through a non-trivial phase in the CKM quark mixing matrix. Interference between the direct decay, $B^0 \to J/\psi K_S^0$, and the decay after mixing ($\overline{B^0} \to B^0$) leads to an asymmetry $A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$. The $B^0 - \overline{B^0}$ mixing frequency is governed by the mass difference, Δm, between the heavy and light mass eigenstates. The proper time of decay, t, is employed in order to achieve maximum sensitivity via a time-dependent measurement of the asymmetry. Previous direct measurements of the asymmetry have been made by OPAL[4] and CDF,[2] the latter result being updated by the analysis presented here.

The CDF measurement of $\sin(2\beta)$ is made possible by the distinctive decay to a final state with all charged particles: $B^0 \to J/\psi K_S^0 \to \mu^+ \mu^- \pi^+ \pi^-$. Charged particle three-momenta are determined at CDF with an 84-layer drift chamber (the CTC) that covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -ln[\tan(\theta/2)]$ and θ is the polar angle angle in a cylindrical coordinate system in which the z axis coincides with the $\bar{p}p$ beam line. The z coordinate of the $\bar{p}p$ interaction is determined with a time projection drift chamber (the VTX) located inside the CTC. The VTX surrounds the silicon vertex detector (the SVX) which consists of four layers of axial silicon strips (providing $r - \phi$ information) located at radii between 2.9 and 7.9 cm and extending ± 25 cm in z from the detector center. The central tracking volume is immersed in a 1.4 T uniform axial magnetic field. The component of charged track momentum transverse to the beam line, p_T, is determined with a resolution of $\delta p_T / p_T = [(0.0009 \cdot p_T^2 (\mathrm{GeV}/c)^2 + (0.0066)^2]^{1/2}$ for tracks well measured in the SVX-CTC.

Electrons and muons are readily distinguished within CDF from other charged particles (pions, etc.) The central tracking volume is surrounded by calorimetry with projective tower geometry which is augmented with a preshower detector and with strip chambers at electromagnetic shower maximum. Electrons are identified by their interactions in the calorimeter and by dE/dx information from the CTC and preshower detectors. Muons in the central region with $p_T > 1.4$ GeV/c typically penetrate

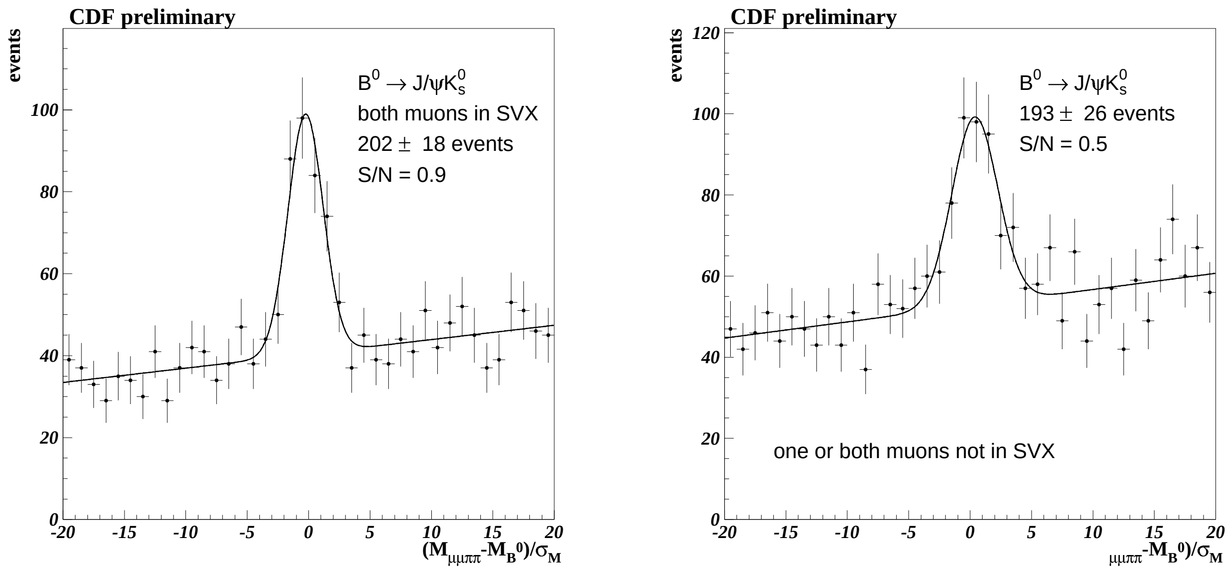

Figure 1: Normalized mass distributions for $J/\psi\, K^0_S$ candidates in the SVX and non-SVX samples.

the calorimeter ($\sim$ 5 absorption lengths) and are detected in central muon chambers (85% coverage in azimuth for $|\eta| < 0.6$). Additional coverage is provided by central muon upgrade chambers (80% azimuthal coverage, after a total of $\sim$ 8 absorption lengths) and central extension muon chambers (67% azimuthal coverage for $0.6 < |\eta| < 1.0$, after a total of $\sim$ 6 absorption lengths).

Candidate events are reconstructed mainly from data collected with a dimuon trigger having a relatively low threshold ($p_T(\mu) > \sim 2$ GeV/c). For events with a reconstructed $J/\psi \to \mu^+\,\mu^-$ decay, K^0_S candidates are formed from pairs of oppositely charged tracks, assumed to be pions, and required to have $p_T > 0.7$ GeV/c and be well separated from the $\bar{\mathrm{p}}\mathrm{p}$ collision envelope. Mass, vertex and pointing constraints are then used in a four particle fit for B^0 candidates.

From 110 pb^{-1} of data collected with CDF the yield of $J/\psi\, K^0_S$ decays is 395 ± 31 events with a signal to background of 0.7 for $p_T(B) > 4.5$ GeV/c. The normalized mass distribution is displayed in Fig. 1 where the data has been divided into two disjoint subsets: an SVX sample (202 ± 18 events with a signal to background of 0.9) and a non-SVX sample (193 ± 26 events with a signal to background of 0.5). The SVX sample is the subset of candidates for which both muons had trajectories well measured in the silicon vertex detector. The sample sizes are roughly equal due to the limited acceptance of the SVX (60%); it's size (± 25 cm) is similar to the $\sim$ 30 cm rms spread in the distribution of $\bar{\mathrm{p}}\mathrm{p}$ interactions along the beam axis.

The SVX sample is essentially the same as that employed for the previously published CDF result [2] on $\sin(2\beta)$. The SVX events have the precise decay length information needed to carry out a time-dependent asymmetry measurement. The non-SVX events have less precisely determined decay lengths, but can nevertheless contribute at least via a time-integrated measurement. In fact 30% of the non-SVX events have one muon well measured in the silicon vertex detector.

In order to measure the asymmetry A_{CP} it is necessary to identify (tag) whether the decaying B meson was initially produced as B^0 or $\overline{B^0}$. The effectiveness of the tag depends on its efficiency (ϵ) and its purity. The purity of a tagging algorithm is usually expressed in terms of a dilution factor or fractional difference of right (R) and wrong (W) tags: $D = (N_R - N_W)/(N_R + N_W)$. An impure tagger with dilution $D < 1$ results in a smaller observable asymmetry: $A^{obs}_{CP} = DA_{CP}$. The statistical uncertainty for the result on $\sin(2\beta)$ is inversely proportional to $\sqrt{\epsilon D^2}$.

Three tagging algorithms are employed in order to maximize the sensitivity of the measurement. All three methods have been developed and used by CDF for $B^0 - \overline{B^0}$ mixing measurements. One of the algorithms employed, a same-side tagging algorithm (SST), exploits charge correlations expected [5]

Table 1: Percentage efficiencies and dilutions as measured for the flavor tagging algorithms employed. For the SST algorithm, the efficiency values include the fractions of SVX and non-SVX events; thus, the tagging efficiency for the total sample is the sum of the SVX and non-SVX efficiencies.

type	tagger	class	efficiency(ϵ)	dilution($\mathcal{D}$)
same-side	same-side	SVX μ	35.5 ± 3.7	16.6 ± 2.2
	same-side	non-SVX μ	38.1 ± 3.9	17.4 ± 3.6
opposite side	soft lepton	all events	5.6 ± 1.8	62.5 ± 14.6
	jet charge	all events	40.2 ± 3.9	23.5 ± 6.9

between the B meson flavor and and the charge of pions produced in fragmentation or from the decays of resonances (B^{**}). The SST algorithm employed with the SVX sample in the analysis reported here is identical to that used in the published analysis [2] on $\sin(2\beta)$ and an associated mixing measurement. [6] Appropriate modifications have been made to validate and apply the SST tag to the non-SVX sample. The expected dilution and efficiency for the SST algorithm then largely follows from the previous work. [2,6]

Two opposite-side tagging algorithms are employed. A soft lepton tagging algorithm (SLT) exploits the correlation of the flavor (b or $\bar{b}$) of the B meson at production with the charge of the lepton from the semileptonic decay of the (opposite-side) b hadron produced in association with it. A jet charge tagging algorithm (JETQ) exploits a similar correlation between the B meson flavor and the momentum weighted sum of charges for a cluster of tracks (a jet) associated with the decay of the opposite-side b hadron. The SLT and JETQ algorithms are very similar to algorithms used in a CDF mixing analysis [7] carried out with a sample of candidate B mesons detected via their semileptonic decays. The B mesons in the mixing analysis sample have a higher p_T (typically a factor of ~ 2) than the $J/\psi K^0_S$ events, and this motivates modifications of the SLT and JETQ algorithms. The expected dilutions and efficiencies for the SLT and JETQ tagging algorithms are determined with a sample of 1000 $B^\pm \to J/\psi\, K^\pm$ decays and a sample of 40,000 inclusive (non-prompt) $J/\psi \to \mu^+\mu^-$ decays. The SLT and JETQ algorithms are applied to both the SVX and non-SVX event samples.

The tags are defined to be essentially orthogonal; in particular, tracks within a cone of $\sqrt{(\eta^2 + \phi^2)} < 0.7$ centered on the vector momentum of the $B \to J/\psi K^0_S$ decay can be candidates for an SST tag but are excluded from use for a JETQ tag. Each event can be tagged by zero, one or two algorithms. In the case of two tags, one must be SST. If both SLT and JETQ tags are present the SLT assignment is taken due to its superior (larger) dilution. Tagging information is obtained for 80% of the events in the $J/\psi K^0_S$ sample. Taking into account single and double tags, a combined effective tagging efficiency $\epsilon D^2 = 6.3 \pm 1.7\%$ is obtained.

An unbinned maximum likelihood [8] fit is used to extract a value for $\sin(2\beta)$. The B^0 lifetime and Δm_d are constrained in the fit to the world average values. The fit includes the SVX and non-SVX samples and treats the decay length uncertainty and dilutions appropriately. The fit allows for prompt and non-prompt background components as well as the possibility of charge asymmetries in the efficiencies and dilutions of the tags. No significant asymmetries are observed in the dilutions or the backgrounds.

The result from the fit is $\sin(2\beta) = 0.79 \pm 0.39(\text{stat}) \pm 0.16(\text{syst})$. The statistical uncertainty dominates and the systematic uncertainty arises almost entirely from the determination of the dilution parameters with the limited sample of $B^\pm$ decays. From this result, a 93% confidence interval of $0.0 < \sin(2\beta) < 1.0$ is obtained for the frequentist approach advocated by Feldman and Cousins. [9] Similar limits are obtained using alternative methods.

The result obtained, $\sin(2\beta) = 0.79^{+0.41}_{-0.44}(\text{stat} + \text{syst})$, provides the best direct indication so far that CP invariance is violated in the b quark system. This result is consistent with the Standard (CKM) Model expectation for a large positive asymmetry. Indirect constraints from measurements of other CKM related quantities suggest that $\sin(2\beta)$ is large and positive: $\sin(2\beta) = 0.75 \pm 0.09$. [10]

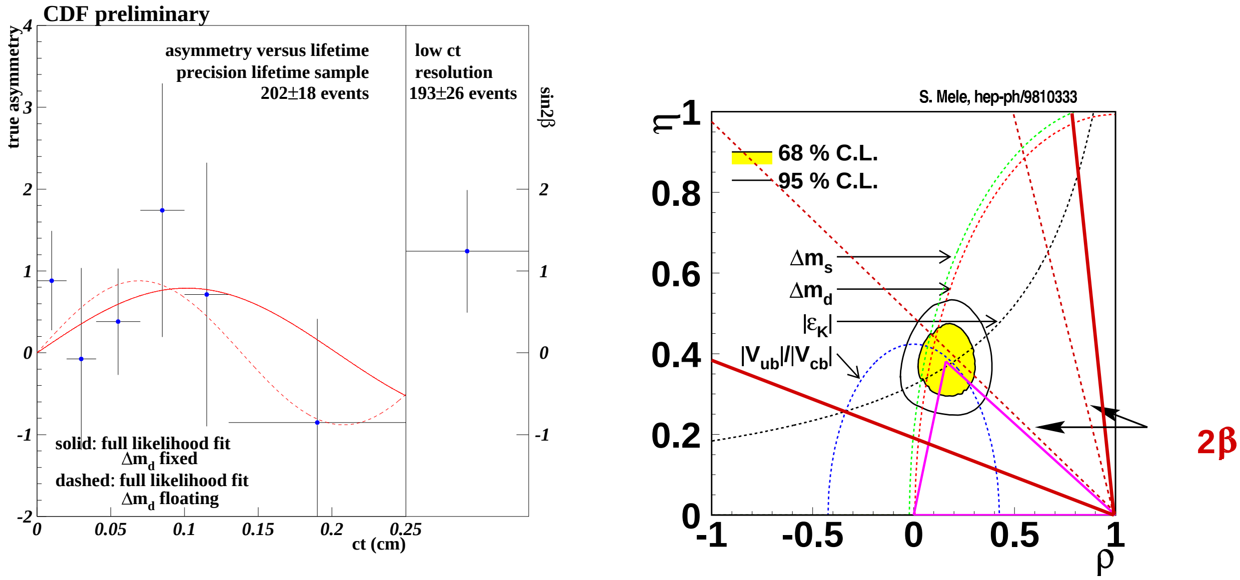

Figure 2: Left: The true asymmetry ($\sin(2\beta)$) as a function of the proper decay length for the $B \to J/\psi\, K^0_S$ events. The data points shown have the effective dilution combined for single and double tagged events after background subtraction. The non-SVX data sample is represented as a single point. The curves are from the full fit using both the SVX and non-SVX data. Right: The measurement of $\sin(2\beta)$ translates into two results (dotted lines) and one sigma bound (solid lines) on β which is displayed on the $\rho - \eta$ plane.

Fig. 2 displays the result on β on the $\rho - \eta$ plane (following Wolfenstein's [11] parametrization of the CKM quark mixing matrix.) It is noted that the expected sign of the asymmetry depends on the relative sign of hadronic matrix elements governing mixing in the $K^0 - \overline{K^0}$ and $B^0 - \overline{B^0}$ systems. [12]

Extrapolating to the anticipated luminosity of 2 fb^{-1} in Run II and assuming no improvements in the effective tagging efficiency, an uncertainty on $\sin(2\beta)$ of ~ 0.08 is expected.[13]

3 Measurement of Polarization Amplitudes in $B^0 \to J/\psi\, K^{*0}$ and $B^0_s \to J/\psi\, \phi$ Decays

The decays $B^0 \to J/\psi\, K^{*0}$ and $B^0_s \to J/\psi\, \phi$ are pseudoscalar to vector-vector decays and in principle have three decay amplitudes which can be determined by studying the angular distributions of the final state particles. These decays can have orbital angular momenta between the J/ψ and K^* (or ϕ) of 0, 1, or 2, and three matrix elements are needed to describe the transitions to these three eigenstates of the $J/\psi\ K^*$ (or ϕ) system. A very useful basis for this description is the transversity basis. [14] In this basis one matrix element, $A_\perp$, corresponds to the parity odd, $L = 1$ (P wave), amplitude, and two matrix elements A_0 and $A_{||}$ are combinations of the parity even, $L = 0$ and $L = 2$ (S and D wave), amplitudes. Also, $|A_0|^2$ is equal to the longitudinal polarization fraction, Γ_L/Γ, as is commonly defined in the helicity basis. [15]

A determination of the longitudinal polarization is relevant to testing the limitations of theoretical predictions which follow from the factorization hypothesis. The factorization hypothesis assumes that the weak decay amplitude can be described as the product of two independent (hadronic) currents. For these decays the factorization ansatz treats the J/ψ as a current independent of the $B \to K^*$ (ϕ) current. One assumes the decay matrix elements factorize naturally into short and long distance (weak and strong) processes which do not interfere with each other. This implies that the matrix elements of the decay be relatively real. The observation of nontrivial phases between the matrix element implies final state interactions (though the absence of nontrivial phases need not rule out the presence of final state interactions).

A measurement of the parity odd amplitude, $A_\perp$, is of interest from the point of view of studies of CP invariance. As discussed earlier, the decay mode $B^0 \to J/\psi K^0_S$ is useful for a determination

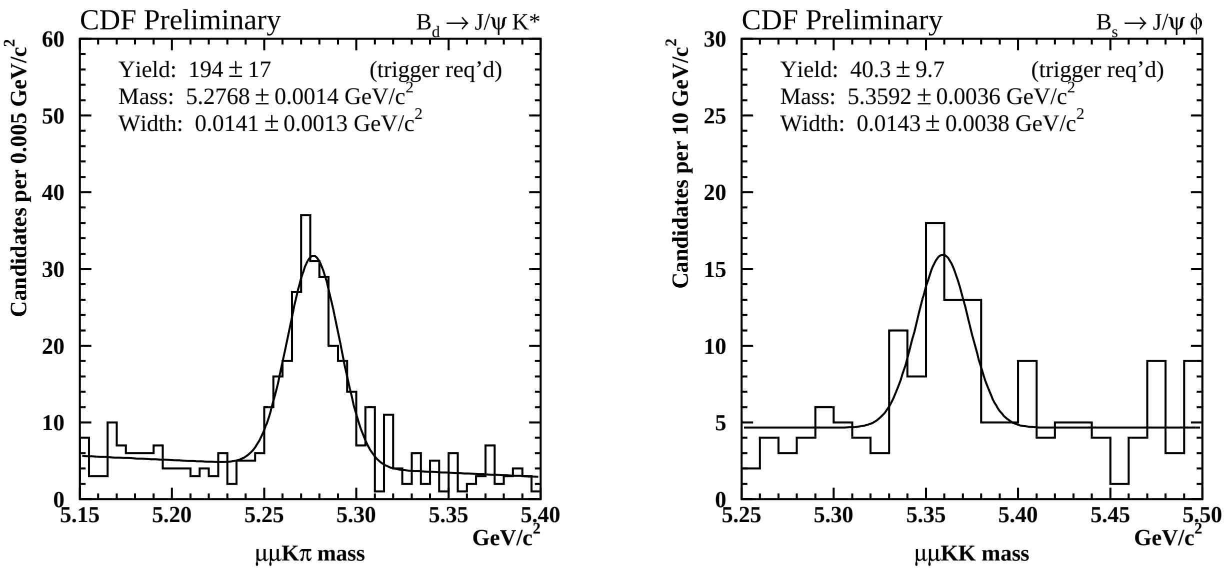

Figure 3: Mass distributions for B_d (left) and B_s^0 (right) candidates used in the polarization analysis.

of $\sin(2\beta)$. This is due to the fact that the final state is a CP eigenstate and one weak amplitude contributes to the decay. The decay $B^0 \to J/\psi\ K^{*0}$ can also be of use, when the final state is a CP eigenstate (*e.g.* $K^{*0} \to K^0_S\ \pi^0$). A measurement of β is most readily extracted if one or the other parity amplitude dominates the decay, otherwise the asymmetry in the decay rates is diluted. The situation holds as well for the decay $B_s^0 \to J/\psi\phi$ which is expected to have a very small CP decay rate asymmetry in the Standard (CKM) Model.

Finally, one of the objectives of studying B_s^0 meson decays is to determine the properties of the $B^0_{s,H}$ and $B^0_{s,L}$ states. Since they are very nearly CP eigenstates, they will decay with distinct angular distributions. This can improve the sensitivity of a lifetime difference measurement by adding information beyond the decay time distribution alone.[16]

The events used in this analysis are selected from a sample in which the muons from the J/ψ decay satisfy dimuon triggers employed during Run Ib (90 pb^{-1}). The event selection criteria are similar in spirit to the $J/\psi K^0_S$ analysis discussed above. The main differences are the requirements for $p_T > 2.0$ (1.5) GeV/c for the K^* (ϕ) and $p_T > 6.0$ (4.5) GeV/c for the B^0 (B_s^0) candidates. Also two of the four charged tracks in each candidate are required to be well measured in the SVX and a minimum proper decay length of 100 (50) μm is required for B^0 (B_s^0) candidates. In principle, this can bias the angular distribution for the B_s^0 since the mass eigenstates are approximately CP eigenstates and can have different lifetimes. The mass distributions of the B candidates are shown in Fig. 3.

The decay angular distribution has the following form, expressed in terms of the decay angles of the decay products of the vector mesons:[14]

$$\begin{aligned}
\Omega_{\rm Trn} \propto \quad & 2\cos^2\Theta_{K^*}\left(1-\sin^2\Theta_{\rm T}\cos^2\Phi_{\rm T}\right)|A_0|^2 + \sin^2\Theta_{K^*}\left(1-\sin^2\Theta_{\rm T}\sin^2\Phi_{\rm T}\right)|A_{||}|^2 \\
+ \quad & \sin^2\Theta_{K^*}\sin^2\Theta_{\rm T}|A_\perp|^2 + \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_{\rm T}\sin 2\Phi_{\rm T}\,{\rm Re}(A_0^* A_{||}) \\
\mp \quad & \sin^2\Theta_{K^*}\sin 2\Theta_{\rm T}\sin\Phi_{\rm T}\,{\rm Im}(A_{||}^* A_\perp) \pm \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_{\rm T}\cos\Phi_{\rm T}\,{\rm Im}(A_0^* A_\perp)
\end{aligned}$$

Note that the last two terms have opposite signs for the decay of a $\bar{B}$ as compared with a B. The B^0 and $\overline{B^0}$ decays are flavor tagged by the charge of the K meson, but the B_s^0 and $\overline{B}_s$ are not distinguishable by their final state particles. Hence, for B_s^0 decays information about the phase of $A_\perp$ is lost.

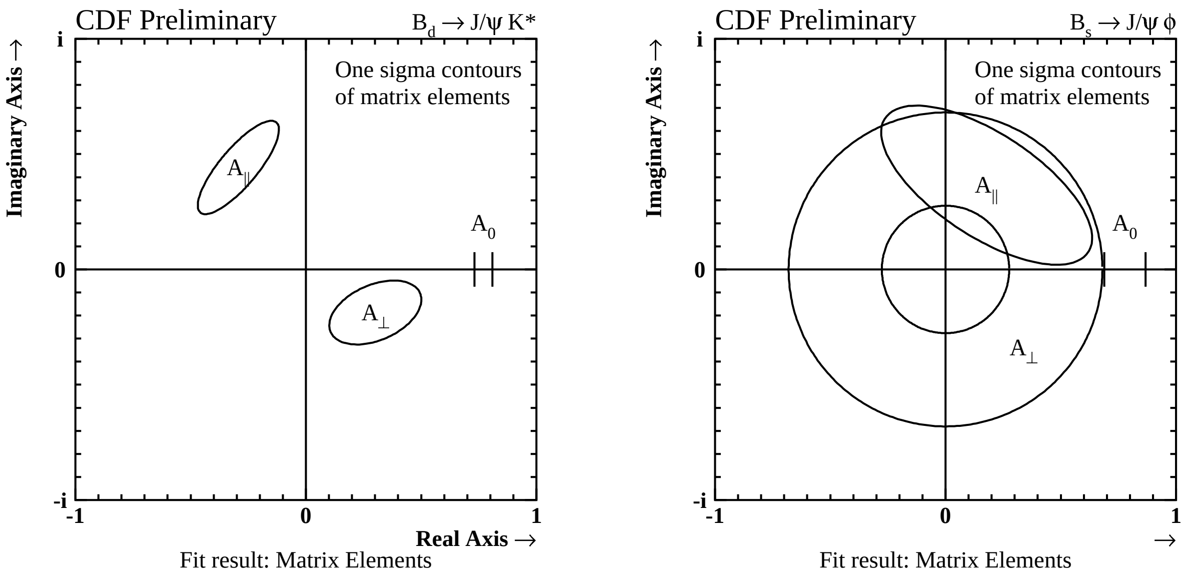

Figure 4: One sigma contours of the fit for the decay amplitudes in the $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$ decay modes; the longitudinal component (A_0) is taken to be real.

The decay matrix elements are extracted from a likelihood fit with care taken into account for the detector acceptance and residual backgrounds.[17] Fig. 4 shows one sigma contours for the extracted decay matrix elements. For the B^0 decay:

$$\begin{aligned} A_0 &= 0.770 \pm 0.039 \pm 0.012 \\ A_{||} &= (0.530 \pm 0.106 \pm 0.034) e^{(2.16 \pm 0.46 \pm 0.10)i} \\ A_\perp &= (0.355 \pm 0.156 \pm 0.039) e^{(-0.56 \pm 0.53 \pm 0.12)i} \end{aligned} \quad (1)$$

and

$$\begin{aligned} |A_0|^2 = \frac{\Gamma_L}{\Gamma} &= 0.593^{+0.059}_{-0.061} \pm 0.018 \\ |A_\perp|^2 = \frac{\Gamma_\perp}{\Gamma} &= 0.126^{+0.121}_{-0.093} \pm 0.028 \end{aligned} \quad (2)$$

and for the B_s^0:

$$\begin{aligned} A_0 &= 0.778 \pm 0.090 \pm 0.012 \\ A_{||} &= (0.407 \pm 0.232 \pm 0.034) e^{(1.12 \pm 1.29 \pm 0.11)i} \\ |A_\perp| &= 0.478 \pm 0.202 \pm 0.040 \end{aligned} \quad (3)$$

and

$$\begin{aligned} |A_0|^2 = \frac{\Gamma_L}{\Gamma} &= 0.606 \pm 0.139 \pm 0.018 \\ |A_\perp|^2 = \frac{\Gamma_\perp}{\Gamma} &= 0.229 \pm 0.188 \pm 0.038 \end{aligned} \quad (4)$$

The B^0 results are of comparable sensitivity to the results from CLEO;[18] comparable magnitudes are obtained for the three matrix elements, but different central values for the phases. The phases observed in the CDF analysis leave open the possibility of non-trivial final state interactions in the decay. The CDF Run Ib result for the longitudinal polarization is in good agreement with the CDF Run Ia result.[19] This is an important result for tests of factorization,[20] especially when considered along with the observed ratio of branching ratios, R= $\mathcal{B}(B \to J/\psi K^*)/\mathcal{B}(B \to J/\psi K)$.[18,21]

The B_s^0 results are the first and only ones available for a full angular analysis. Again the Run Ib result for the longitudinal polarization is in agreement with that from Run Ia.[19] Comparison of the B^0 and B_s^0 results indicates that $SU(3)_{\text{flavor}}$ is a valid approximation. The decays are dominated by the parity even amplitudes but a non-trivial parity odd component is not yet excluded.

4 Conclusions

New results have been presented for a measurement of $\sin(2\beta)$ from $B^0 \to J/\psi K_S^0$ decays and for full polarization analyses of the decays $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\,\phi$. Besides being of interest in themselves, these results whet the appetite for the richness of the CDF program on b physics during Run II, scheduled to start in the summer of 2000.

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